PCB Material Selection for RF, Microwave and Millimeter-wave Design

Outline

- **Printed Circuit Board (PCB) attributes for RF, microwave, millimeter-wave systems**
- **Application example – Advanced Automotive Safety System**
- **PCB material product solutions**
- **Summary**

RF/Microwave/mm-Wave Trends

- **Aerospace and defense applications are the foundation for RF/microwave/millimeter-wave PCBs**
- **Recent surge in RF/microwave/millimeter-wave commercial applications**
  - Result is wider range of PCB product offerings meeting a wider range of needs
- **Choosing the appropriate PCB material requires consideration of technical performance attributes and cost**

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Considerations for PCB Material Selection

- **System Requirements**
  - Frequency of operation, bandwidth and power
  - Electrical size of board and critical features
  - System loss requirements
  - Temperature range of system operation and cycle profile
  - Number of layers of PCB
- **PCB Material**
  - Electromagnetic loss, mechanical strength, thermal properties
  - Stability over varying environmental conditions – temperature, humidity, etc.
  - RF-power handling capability
  - Processability and compatibility with hybrid constructions
  - Cost

RF/Microwave/millimeter-Wave vs HSD

- **RF/microwave/millimeter-wave PCBs traditionally have only a few layers, in some cases just 1 or 2**
- **PCBs for high-speed digital applications often have 20+ layers with hundreds of traces**
- **RF/microwave/millimeter wave systems require very low loss**
  - Process low-level signals
  - Enable high-power applications
- **HSD applications can be more tolerant of losses**
- **RF/microwave/millimeter-wave system applications generally require very precise control of critical dimensions on the PCB**
- **Boards with RF/microwave/millimeter-wave and HSD functionality present unique challenges but are becoming more common**

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PCB Laminate Material Considerations

- **PCB laminates considered here consist of one or more plies of resin-impregnated glass cloth sandwiched between two copper foils**

- **The RF/microwave/millimeter wave performance of the laminate & resulting PCB depends primarily on**
  - The resin and glass characteristics, dielectric constant and loss factors
  - The quality of the copper foil – surface roughness, purity

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Desirable PCB Electrical Properties

- **Low dissipation factor, Df = tanδ**
  - Maximize power delivered
  - Enable high-power applications
- **Low dielectric constant, Dk**
  - Allows rapid signal propagation
- **Consistent Df, Dk over operating bandwidth of intended application**
  - Provides consistent transmission line impedance
  - Prevents phase distortion
- **Consistent Df, Dk with changes in temperature**

Electrical Loss Effects

Electrical Losses in the PCB result in performance degradation in antennas and transmission lines and components

- **Antenna**
  - Lower radiated power
  - Reduction in gain
  - Broadening of return loss resonance
  - Thermal effects at high power levels

- **Transmission Lines**
  - Lower delivered power
  - Thermal issues in high power applications

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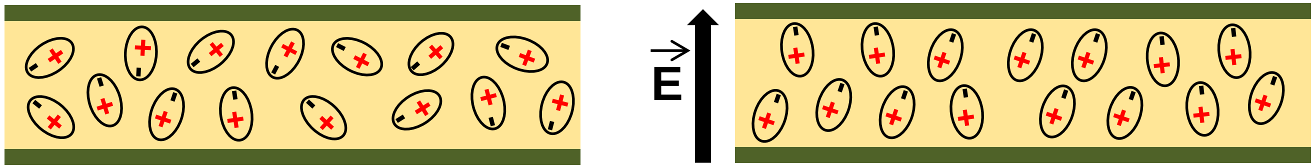
Transmission Line Loss Effects

Microstrip line is dominate transmission line in RF/microwave/mm-wave with performance limited by:

- **Dielectric Loss**
- **Conduction Loss**
- **Mismatch Loss**

PCB Material Dielectric Loss

- Dielectric materials have polarized molecules that move when subjected to the electric field of a digital signal



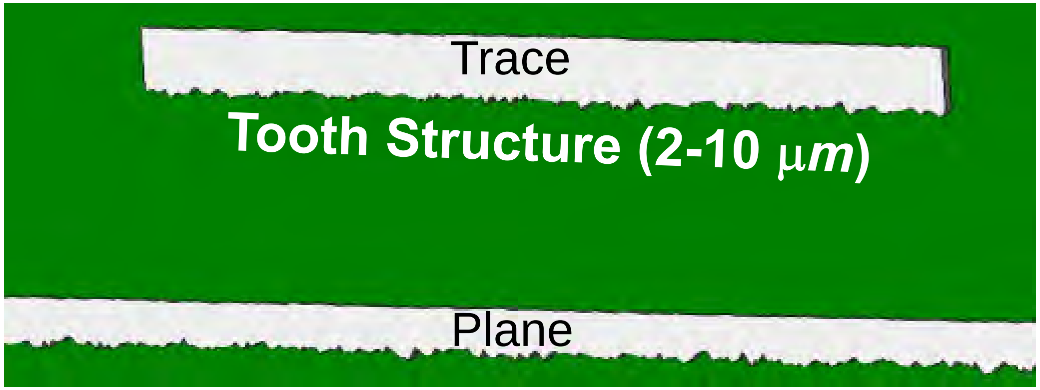
- This motion produces heat loss
- Loss results in signal attenuation that increases in direct proportion to signal frequency

PCB Material Conduction Loss

- **The copper contributes to overall loss through the metal's resistive losses**
- **At high signal frequencies, the current in PCB copper is concentrated within a small depth near its surface (skin effect)**
- **Reduction in effective cross-sectional area increases the effective resistance**

Conductor Surface Roughness

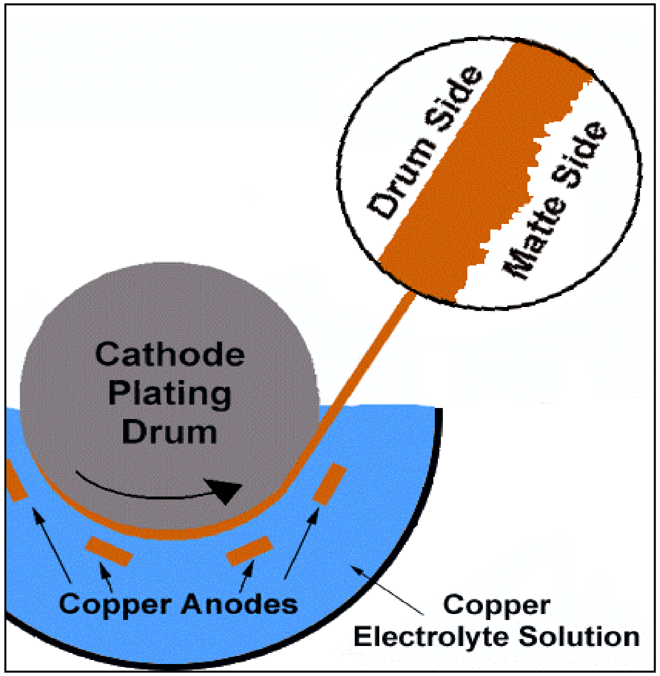
- Conductors on PCBs do not have perfectly smooth surfaces
- Rough copper improves peel strength of laminate
- Maximum peak-peak tooth size varies ≈2-10 microns
- Surface roughness increases bulk copper resistance 10 to 50%
- Electrical impact of conductor roughness increases with increasing frequency



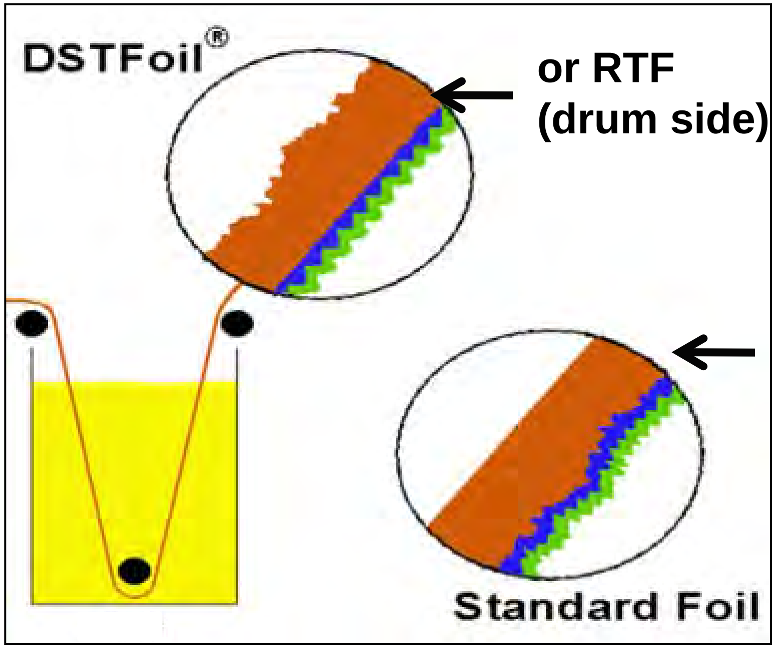
Frequency	Skin Depth (Copper)
50 Hz	9.3 mm
10 MHz	21 μm
100 MHz	6.6 μm
1 GHz	2.1 μm
10 GHz	0.66 μm

Copper Foil Plating

Foil is fabricated by plating copper on a drum



Foil Treatment

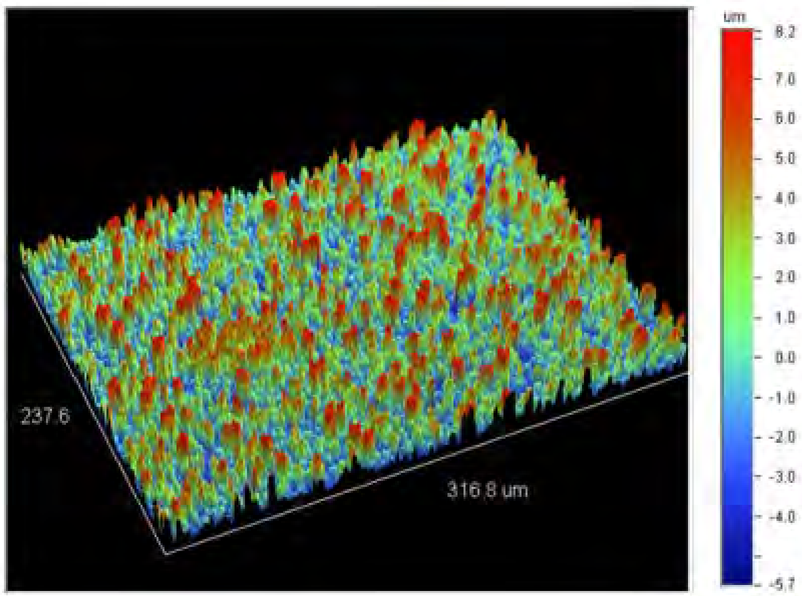


RTF ≠ a foil roughness designator

RTF and VLP Copper Profiles

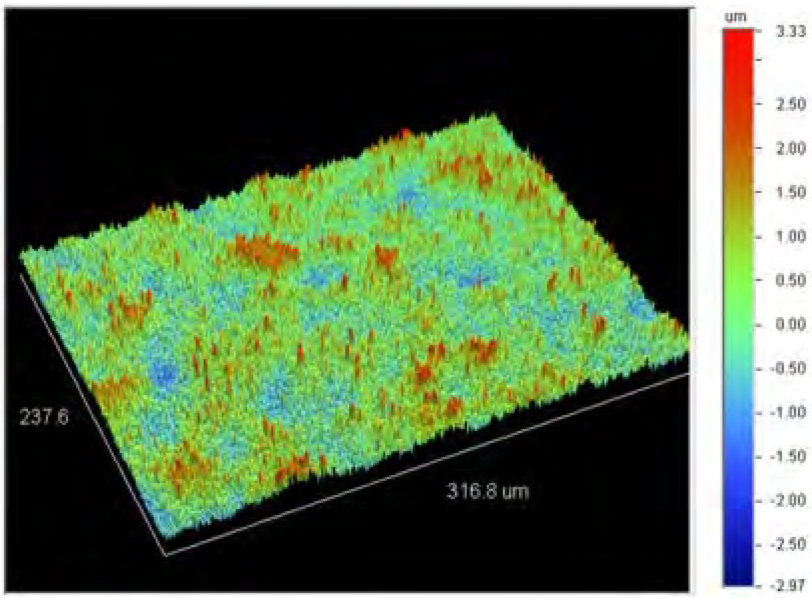
RTF

Rq = 2.6 um, RF = 1.85



VLP

Rq = 0.68 um, RF = 1.3



- Roughness parameters measured with profilometer

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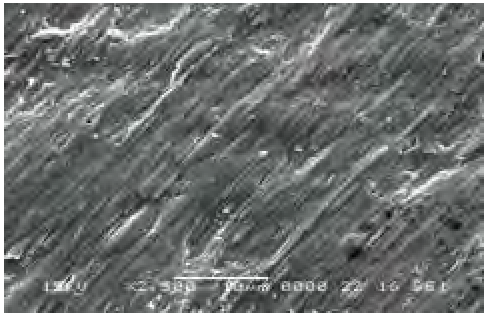
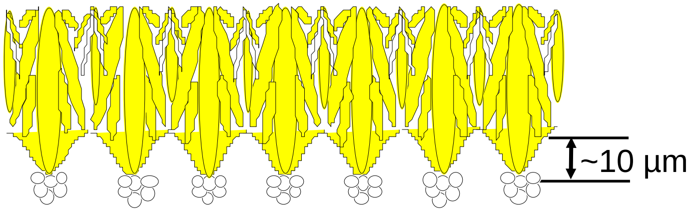
Conductor Surface Roughness

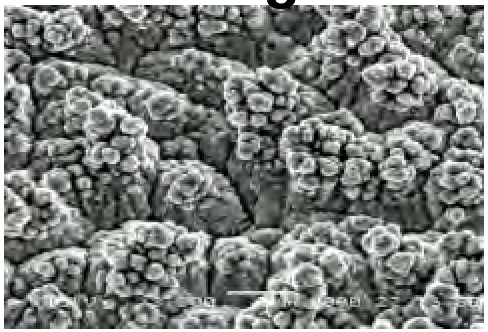
Resist side



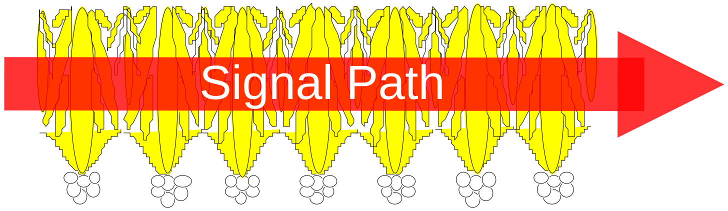
Standard foil



Bonding side

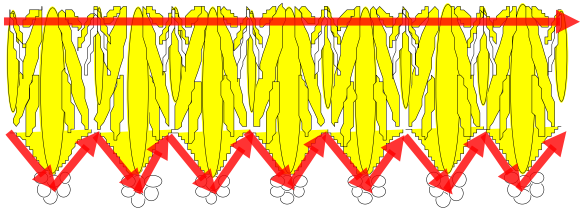


Frequency	Skin Depth
10 MHz	21 µm



The current is able to tunnel below the surface profile and through the bulk of the conductor

Frequency	Skin Depth
100 MHz	6.6 µm



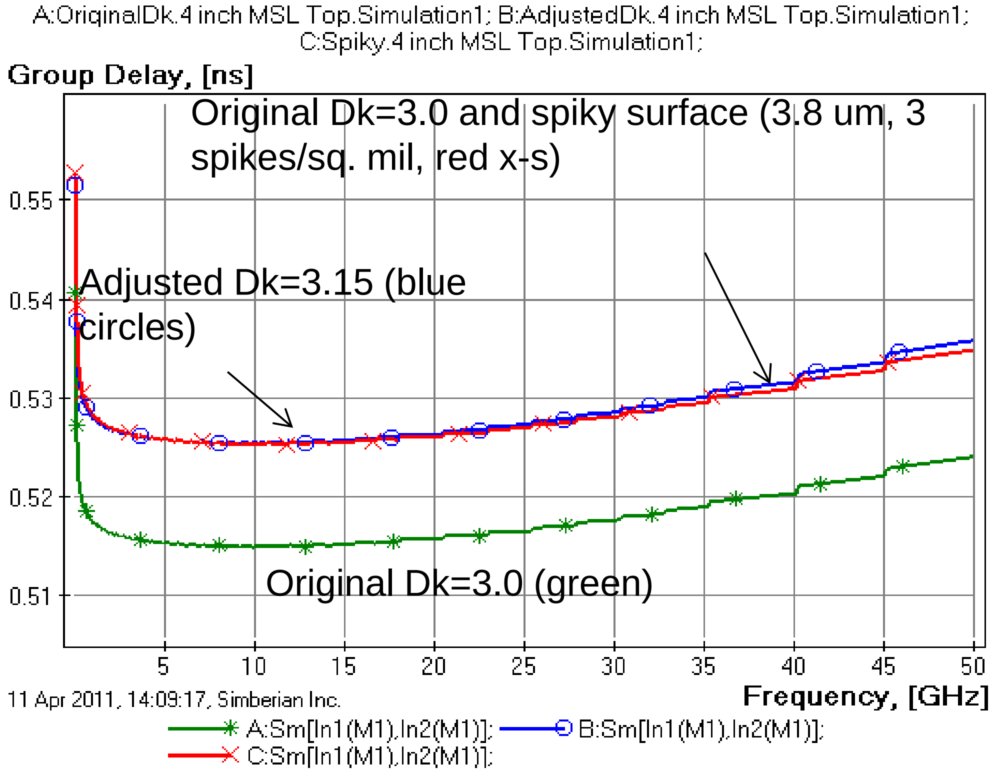
The current is forced to follow every peak and trough of the surface profile increasing path length and resistance

Effects of Surface Roughness

- **Increase in capacitance due singular electric fields on surface spikes**
- **Increase in signal group delay over perfectly smooth**
- **“Apparent” increase in Dk to match group delay vs frequency characteristics**

Example with RTF Foil

- **Multiple spikes are about 10 um from top to bottom**
- **Electric field is singular on the spikes (similar to strip edges)**
- **Consistent for 2 line types**
  - **About 5% increase for MSL with one RTF surface**
  - **>10% increase for strip line with two RTF surfaces**
- **Consistent increase in group delay and decrease in characteristic impedance over very wide frequency band**



With the adjusted Dk of 3.15 the group delay matches that of Dk = 3.0 case with RTF copper surface profile

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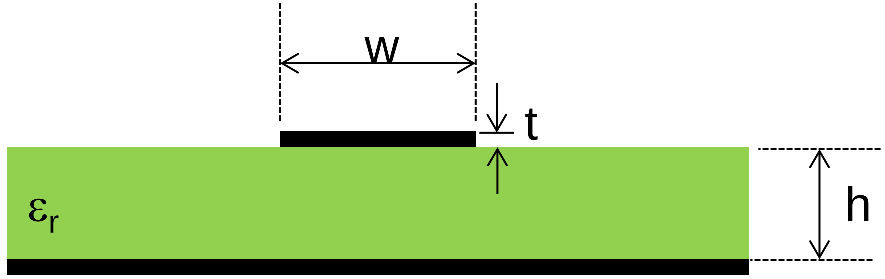
Transmission Line Effects

- **Microstrip Transmission Line**



- **Microstrip Dielectric Loss**

$$\alpha_d = 27.3 \frac{\varepsilon_r(\varepsilon_{eff} - 1)\tan\delta}{\varepsilon_{eff}^{1/2}(\varepsilon_r - 1)\lambda_0} \quad \text{(dB/m)} \text{ [1]}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{(1 + 12h/w)^{1/2}} \quad \text{(static effective permittivity)}$$

$$\varepsilon_{eff}(f) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{eff}}{1 + Gf^2/f_p^2} \;,\quad f_p = \frac{Z_c}{2\mu_0 h} \;,\quad G = 0.6 + 0.009\frac{Z_c}{ohm}$$

Getsinger effective permittivity)

Attenuation constant is linear with respect to loss tangent and can be significant contributor when tanδ ~ 0.005 - 0.01

Transmission Line Effects

- **Microstrip Conductor Loss**

$$\alpha_c = 8.68 \frac{R_s}{Z_c h} \alpha_c' \quad \text{(dB/m)}$$

with $\alpha_c' = f(w_{eq}, h, t)$ [1]

$w_{eq} = w + (t/\pi)(\ln a + 1)$, $a = 4\pi w/t$, $w/h < 1/2\pi$

$w_{eq} = w + (t/\pi)(\ln b + 1)$, $b = 4h/t$, $w/h > 1/2\pi$

$R_s = (\omega\mu/2\sigma)^{1/2}$

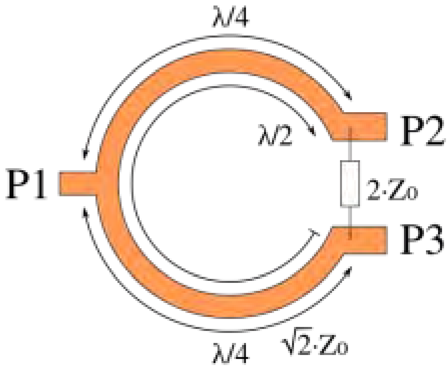
To take surface roughness into account replace Rs with the following

$R_s(\Delta) = R_s\left(1 + (2/\pi)\tan^{-1}(1.4(\Delta/\delta)^2)\right)$ [2]

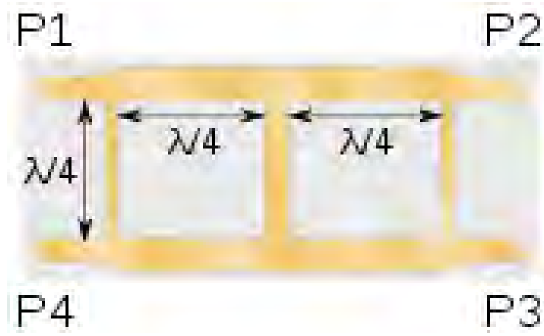
Δ = root mean square surface roughness, δ = skin depth

[1] Noyan Kinayman, *Modern Microwave Circuits*, Norwood, MA, Artech House, 2005
[2] E. Hammerstadt, O. Jensen, “Accurate Models for Microstrip Computer-Aided Design”, *IEEE MTT-S Digest*, vol. 80, pp407-409, May 1980

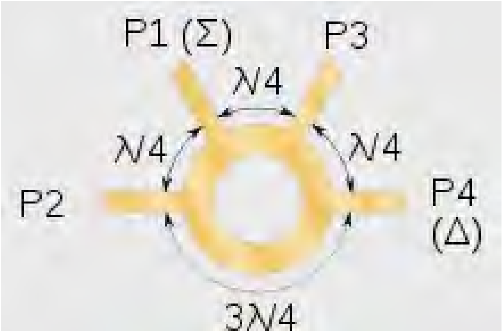
PCB Microwave Component Scales



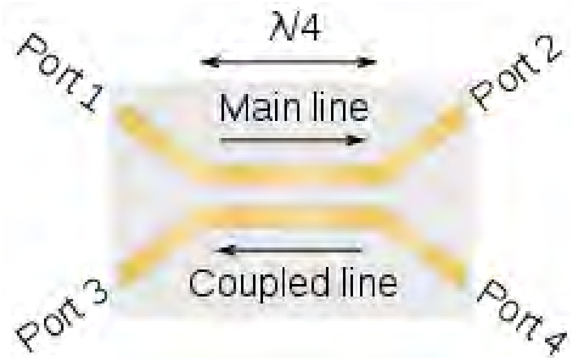
Wilkinson Power Divider



Branch-line coupler



Hybrid Ring Coupler



λ/4 wave directional coupler

- **Microwave circuit elements commonly have λ/4 critical dimensions**
- **Several are typically cascaded requiring propagation distances on order of λ's**
- **System signal loss due to dielectric and conductor losses can be significant**

Transmission Line Effects

- **Microstrip Characteristic Impedance**

$$Z_c = \frac{120\,\pi}{(\varepsilon_{eff})^{1/2}[\,w/h + 1.393 + 0.667\ln(w/h + 1.444)]} \quad \text{for} = w/h > 1$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\,\frac{1}{(1 + 12h/w)^{1/2}} \quad \text{(static effective permittivity)}$$

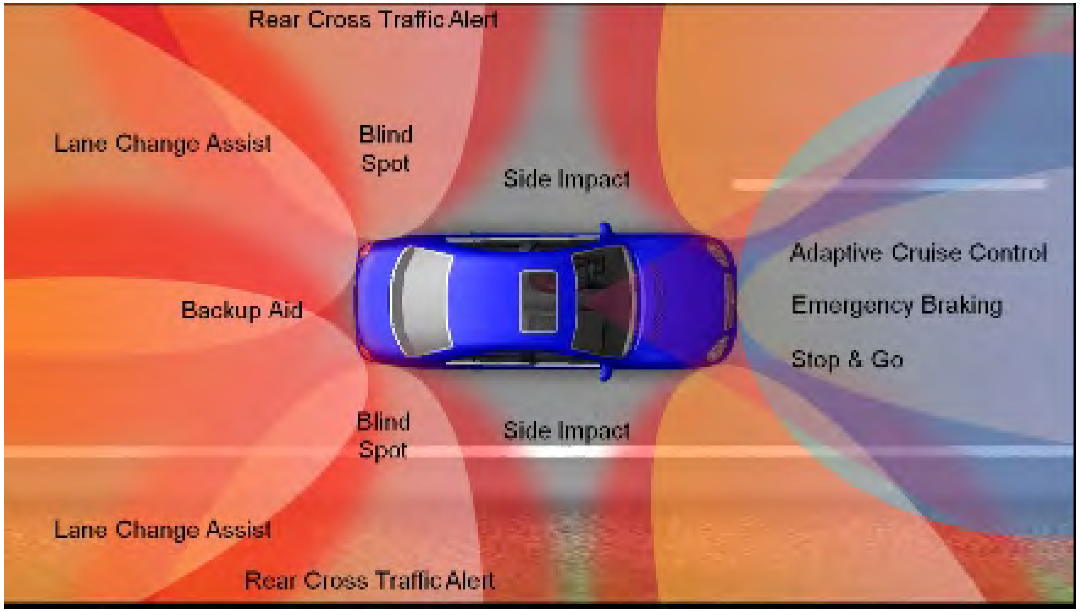
$$\varepsilon_{eff}(f) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{eff}}{1 + Gf^2/f_p^2}\ ,\quad f_p = \frac{Z_c}{2\mu_0 h}\ ,\quad G = 0.6 + 0.009\frac{Z_c}{\text{ohm}}$$

Getsinger effective permittivity)

- **Variations in ε_r result in impedance mismatches**
  - **Variations in dielectric thickness and dielectric properties**
    - **Manufacturing tolerances**
    - **Temperature and frequency dependent dielectric constant and loss factor**
  - **Variations in conductor geometry**

Advanced Automotive Safety Systems

Active Safety Systems



Radar sensor portfolio

- 25 GHz ultra-wide band RADARs
- 24 GHz narrow-band RADARs
- 77 GHz multimode RADARs

Supporting

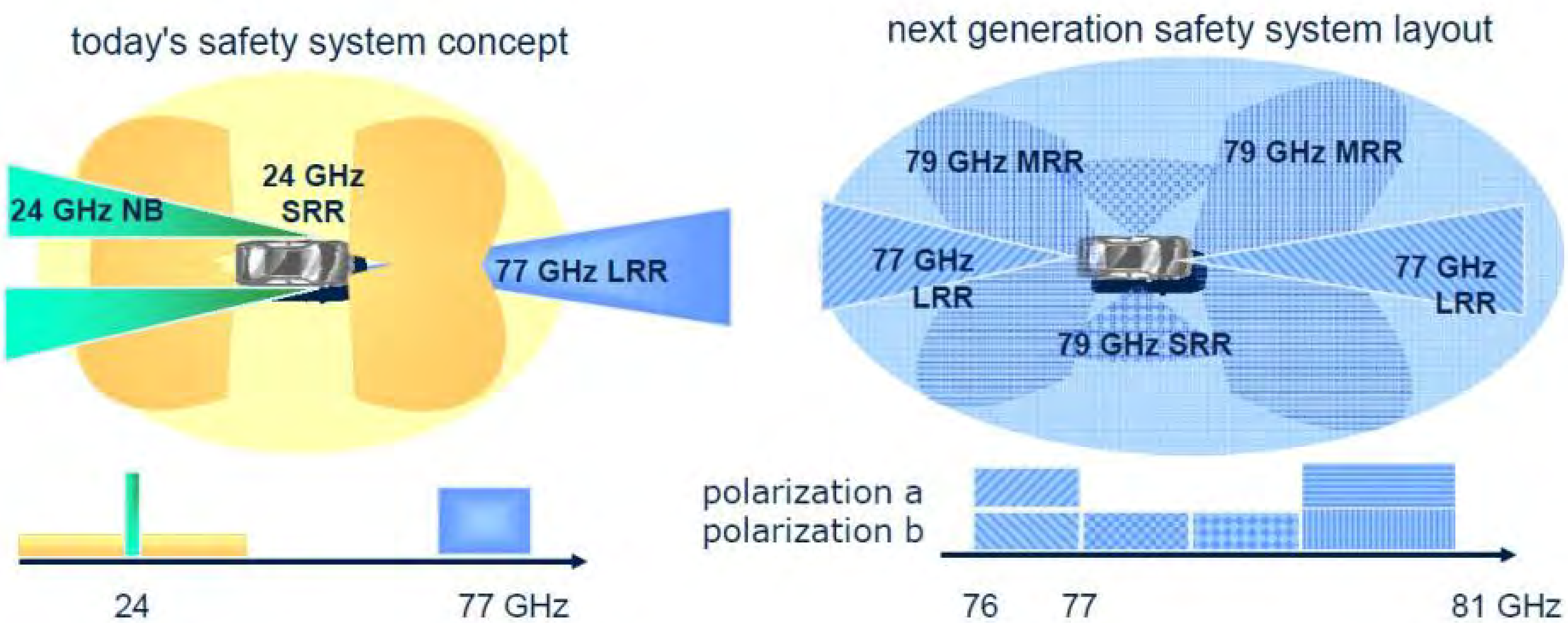
- Blind spot detection
- Rear cross-traffic alert
- Lane change assist
- Forward collision warning
- Autonomous emergency braking
- Adaptive cruise control

RADAR Resolution Requirements

- **Scenarios Requiring High Resolution**
  - Side impact
  - Cross-traffic alert
  - Narrow pass assistant
  - Evasion maneuver
  - Pedestrian protection
  - Front collision warning
  - Proximity warning and parking assistant
- **Scenarios Needing Lower Resolution**
  - Adaptive cruise control – long range
  - Lane change assist – 24 GHz

Frequency	Bandwidth	Resolution
24 – 24.25 GHz	250 MHz	0.6m
21 – 26 GHz	5 GHz	0.03m
76 – 77 GHz	1 GHz	0.15m
77 – 81 GHz	4GHz	0.0375m

Active Safety System Development



Source: Infineon

Systems are migrating to higher frequencies

- **Change in frequency allocation**
- **Improved Performance**
- **Reduced size and improved affordability**

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Active Safety System Trends

- **Shift to higher frequencies**
  - 76 GHz to 81 GHz
  - Development ongoing at 140 GHz
- **Integration of multiple system functions in one chipset**
  - RADAR front end
  - Microcontroller
- **Reduction in system size**
- **Increasing demand for system cost reductions for a widening target market**

PCB Material Selection

- **Frequency of operation requires high performance material**
- **Dk, Df as flat as possible over range of frequency for LRR and SRR**
- **Dk, Df temperature stable over operating range (-40°C to 85°C)**
- **Lowest cost as possible**
  - Choose sufficient material to satisfy requirements
  - Hybrid construction
  - Process compatible with hybrid

Hybrid Construction for Automotive Radar

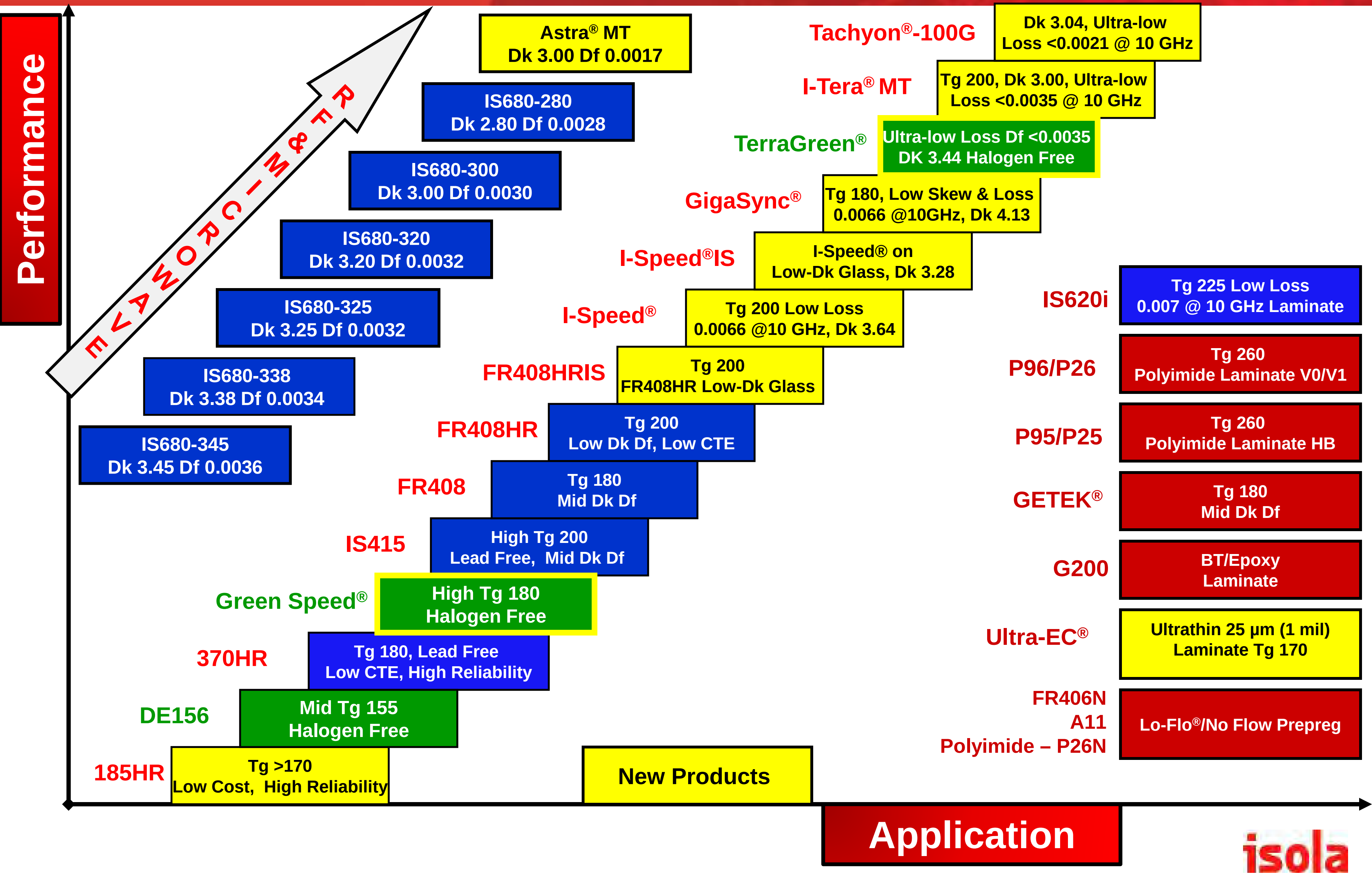
Material : Astra/370HR

		Structure (Stack up)			
Layer	Type		Cu weight (oz)	Construction	Thickness after lam (mil)
1	TOP		0.5 + plating		2.1
	core			Astra - 5 mil Core	5.0
2	V2		0.5		0.6
	prepreg			370HR - 2x1080 68%RC	7.2
3	V3		1		1.3
	core			370HR - 2x7628+2116 45%RC	18.0
4	V4		1		1.3
	prepreg			370HR - 2x1080 68%RC	7.2
5	V5		0.5 + plating		2.1
				Pressed thickness	**44.7**

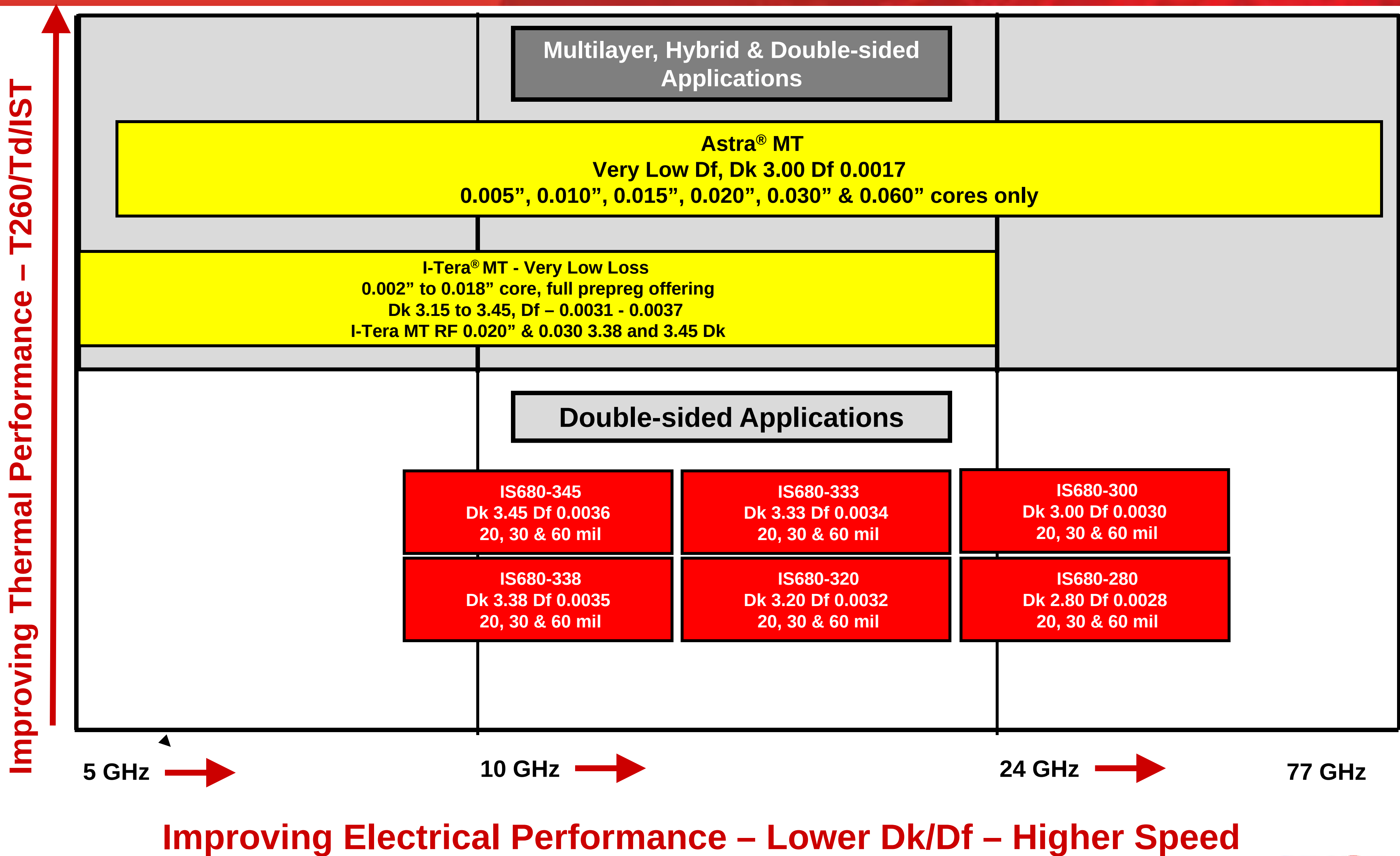
This hybrid structure utilizes high performance material where necessary and standard process-compatible materials to reduce cost

Isola Product Solutions

Isola Product Offering



Isola Product Positioning RF/Microwave Products



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RF/Microwave Product Offerings

- **IS680**
- **I-Tera® MT**
- **Astra® MT**

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IS680

IS680 Product Strengths

- IS680 is available in 0.020”, 0.030” and 0.060” thicknesses
- Typical solder floats > 3000 seconds
- Superior drilling performance – IS680 does not contain a ceramic filler!
- IS680 has been granted a UL 94 V-0 Flammability Rating
- MOT 110°C

IS680 Electrical Properties

- Stable Df over Frequency 2 to 20 GHz
- Stable Df over temperature from -40°C to 125°C
- Stable Dk over frequency range of 2 to 20 GHz
- Stable Dk over temperature from -40°C to 125°C
- Customized Dk on thick cores for different applications (ie. 2.80, 3.00, 3.20, 3.33, 3.38, 3.45)
- The ability to customize Dk to match competitive products vs. advertised Dk values on certain thicknesses
- Excellent power handling ability

IS680 Product Positioning

- **Applicable for RF/microwave designs**
  - LNB (satellite TV)
  - Antenna
  - Power amplifier
  - Traffic sensors
  - RFID
  - Collision warning
  - Base station
  - Base Station antenna
  - Sat telephone
  - WiMAX antenna
- **Capable of meeting lead-free requirements**

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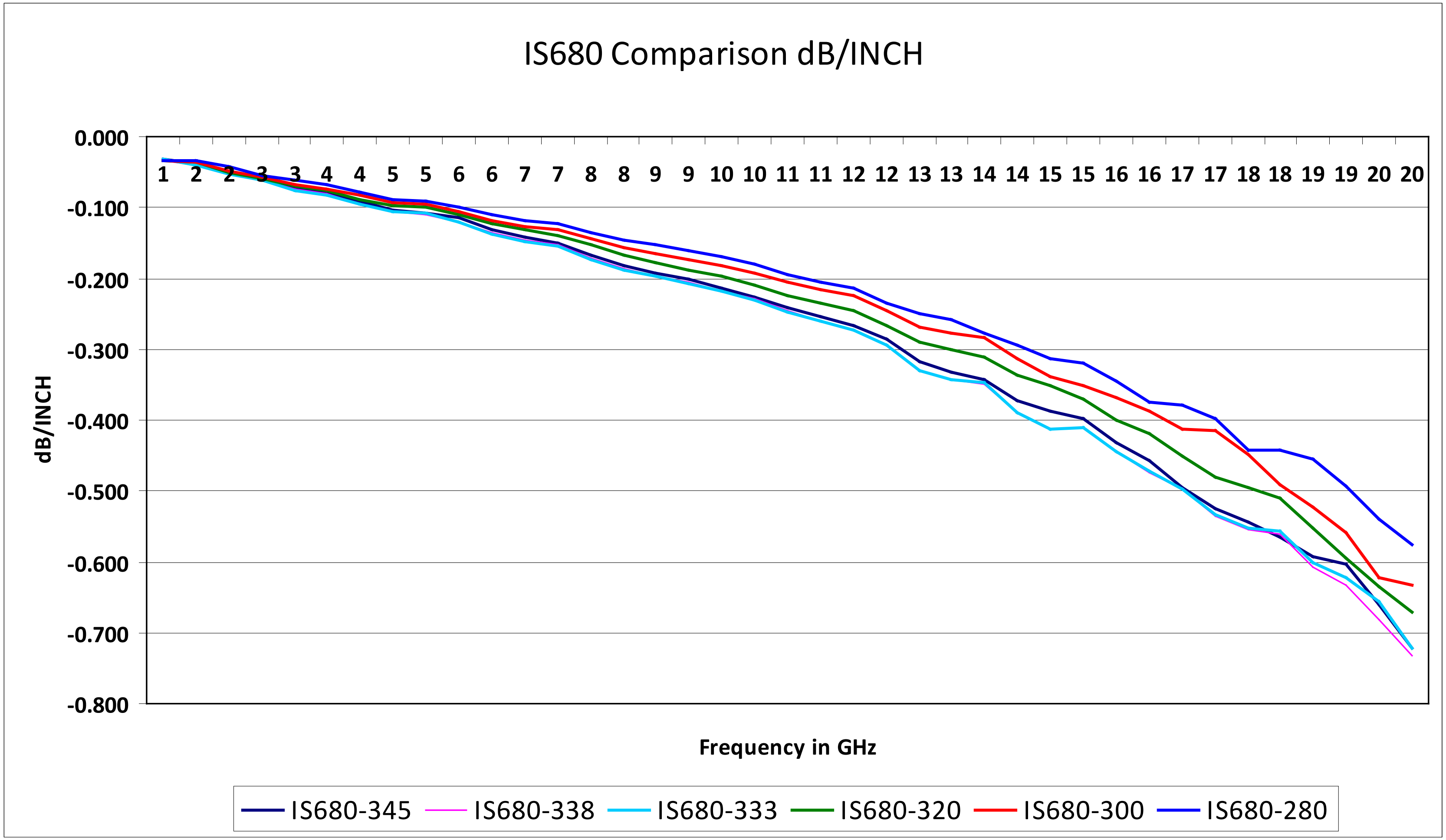
IS680 Typical Material Properties

Property	Units	IS680
Tg, (DSC)	C	200
Td, (TGA - ASTM)	C	360
CTE - z-axis (50-260°C)	%	2.80
T-260 (TMA)	minutes	60
T-288 (TMA)	minutes	> 60
Dk - 2 GHz		2.80 - 3.45
Dk - 5 GHz		2.80 - 3.45
Dk - 10 GHz		2.80 - 3.45
Df - 2 GHz		0.0028 - 0.0036*
Df - 5 GHz		0.0028 - 0.0036*
Df - 10 GHz		0.0028 - 0.0036*
Peels, 1 oz after thermal stress		5
Moisture Absorption	%	0.01
Flammability	-	94 V - 0
UL recognition		non-Ansi

IS680 dB/inch Data



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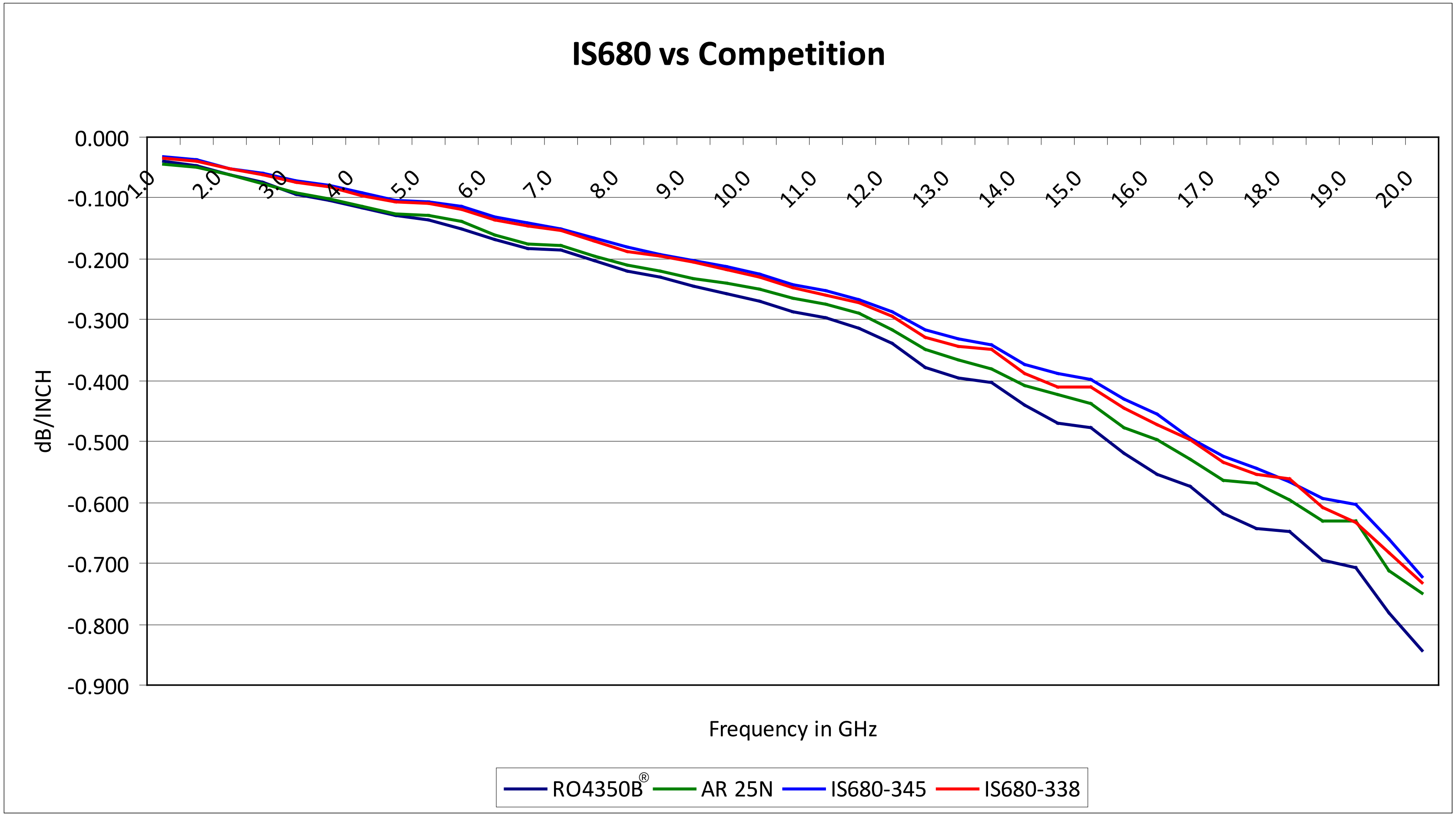
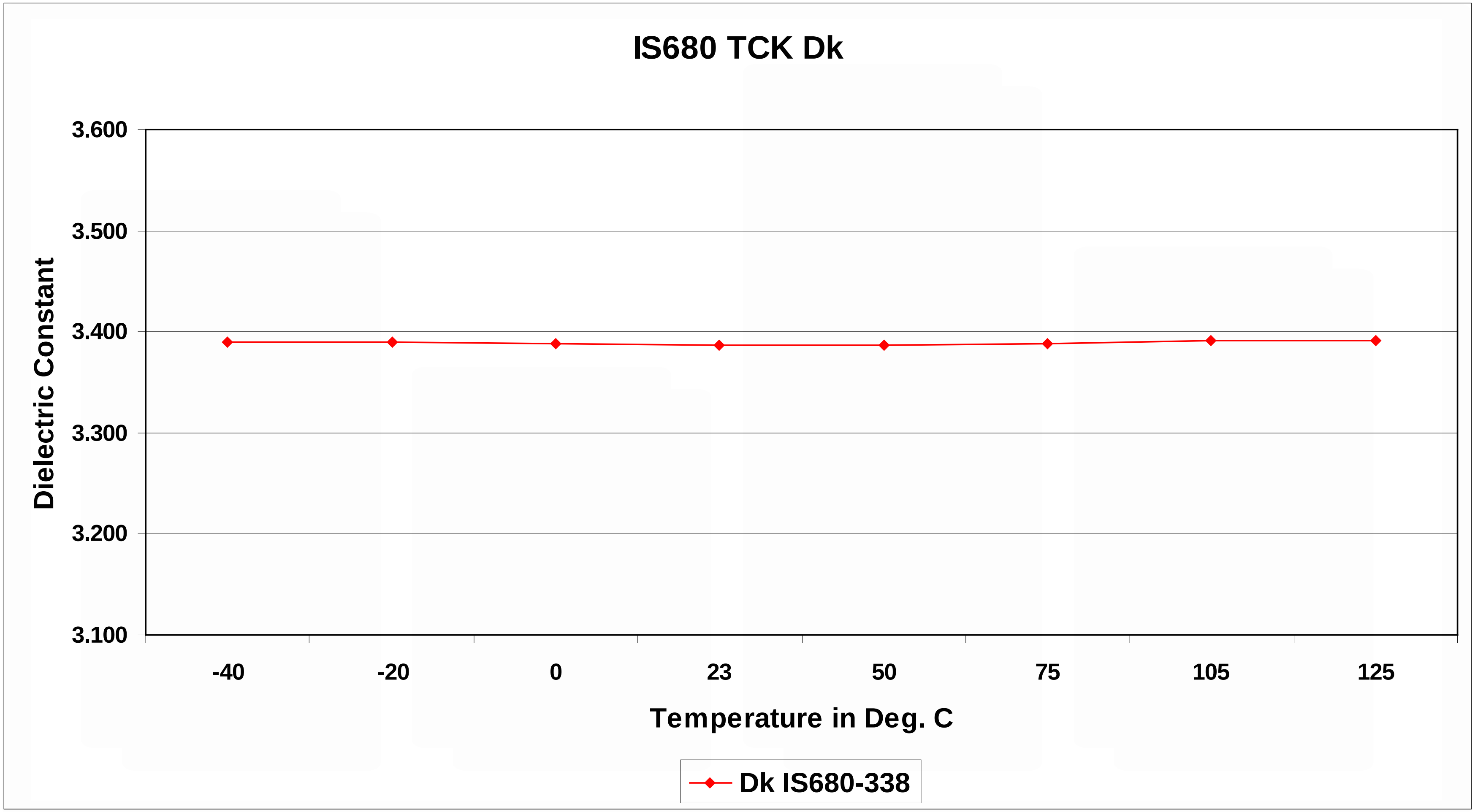
IS680 vs Competitive Products



IS680

TCK Data
Temperature range
-40°C to +125°C at 10 GHz

IS680 TCK Dk -40°C to 125°C



Total delta on Dk of 0.005 – very stable over the temperature range

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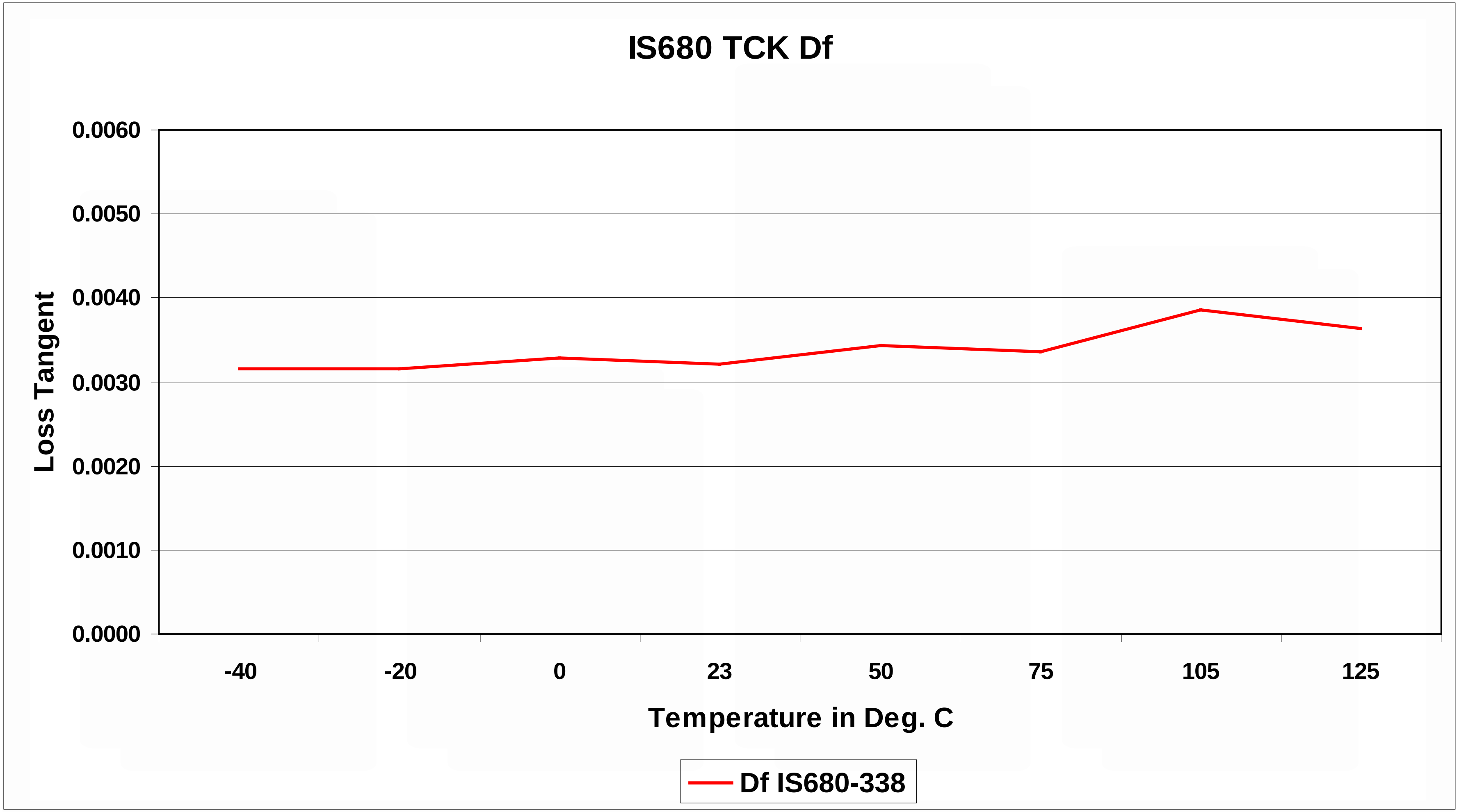
IS680 TCK Df -40°C to 125°C



Very stable Df (loss tangent) over the temperature range

I-Tera® MT

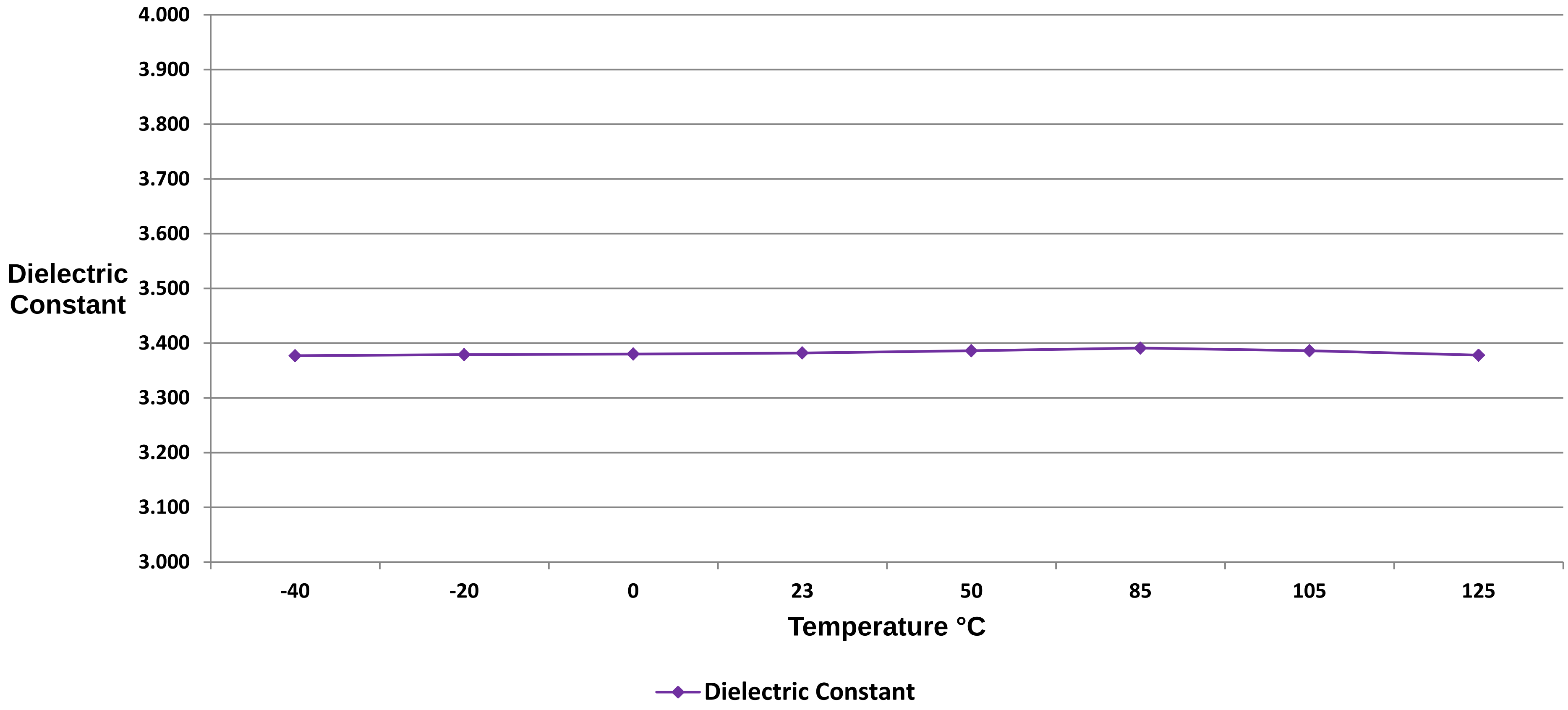
I-Tera® Product Strengths

- Standard thicknesses available (nominal ± 5% for 0.020” and above)
- Full thin core offering from 0.0020 (non-ZBC) to 0.018” for multilayer designs
- I-Tera MT RF 0.020” & 0.030” available for multilayer or hybrid-multilayer designs
- Square and MS-spread glass weaves used: 1035, 1067, 1086, 1078
- Very-low loss material for backplane, high data rate daughter cards, hybrid applications
- Superior drilling performance – I-Tera MT does not contain a ceramic filler
- Processing to date – plasma desmear not required
- No issues with ENIG in testing to date.
- Passed 1000 HATS cycles
- Passed 10x 700°F re-work simulation testing
- Compatible with Isola 185HR, 370HR and IS415 for hybrid constructions
- I-Tera MT prepreg can be stored at standard FR-4 conditions
- UL: 94 V- 0
- UL MOT: 130°C, I-Tera MT is the UL designation

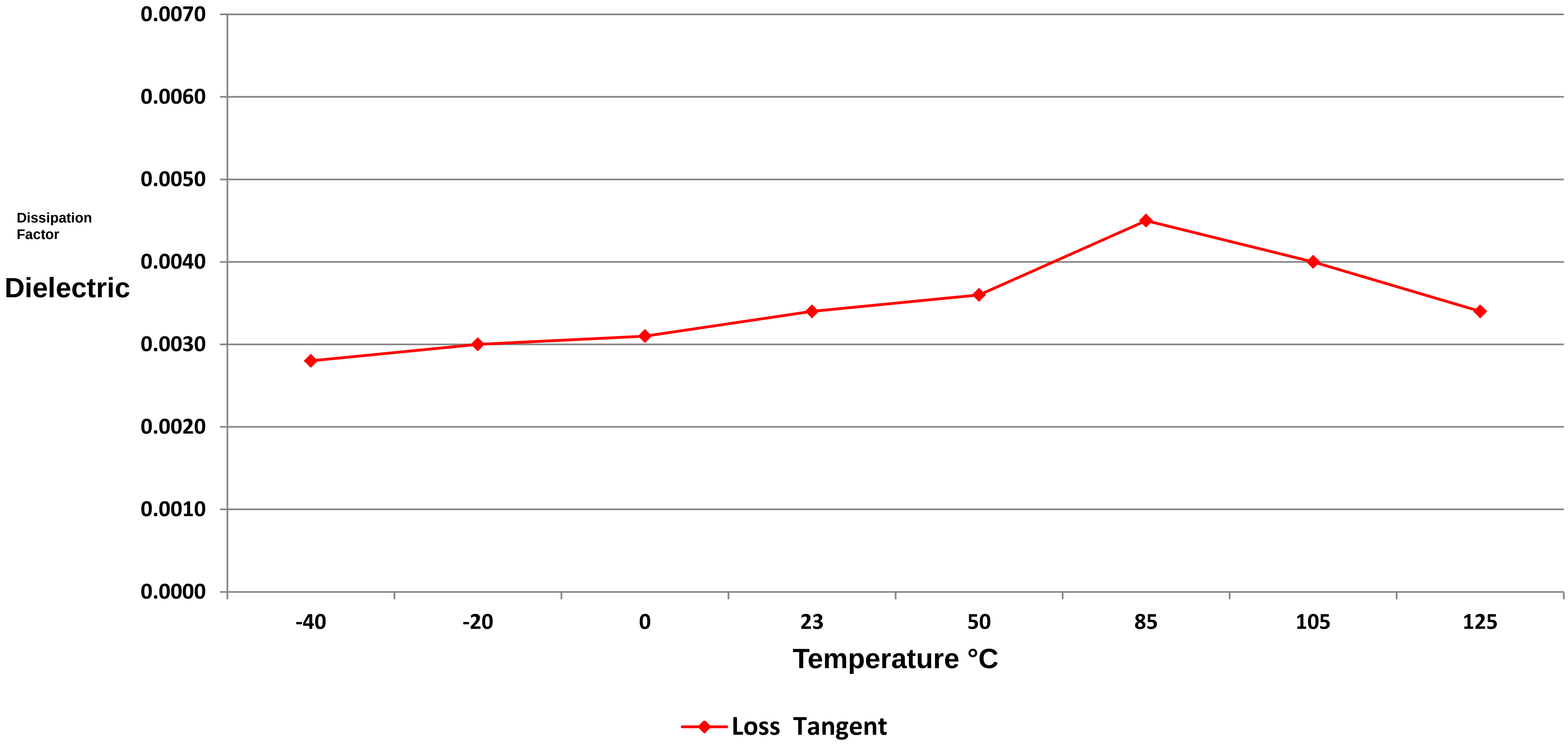
I-Tera® MT Typical Material Properties

Property	Units	I-Tera®MT
Tg, (DSC)	C	200
Td, (TGA)	C	360
CTE - z-axis (50-260 C)	%	2.80
T-260 (TMA)	minutes	60
T-288 (TMA)	minutes	> 60
Dk - 2 GHz		3.00 - 3.45
Dk - 5 GHz		3.00 - 3.45
Dk - 10 GHz		3.00 - 3.45
Df - 2 GHz		0.0030 - 0.0035
Df - 5 GHz		0.0030 - 0.0035
Df - 10 GHz		0.0030 - 0.0035
Peels, 1 oz after thermal stress		5
Moisture Absorption	%	0.01
Flammability	-	94 V-0
UL recognition		non Ansi

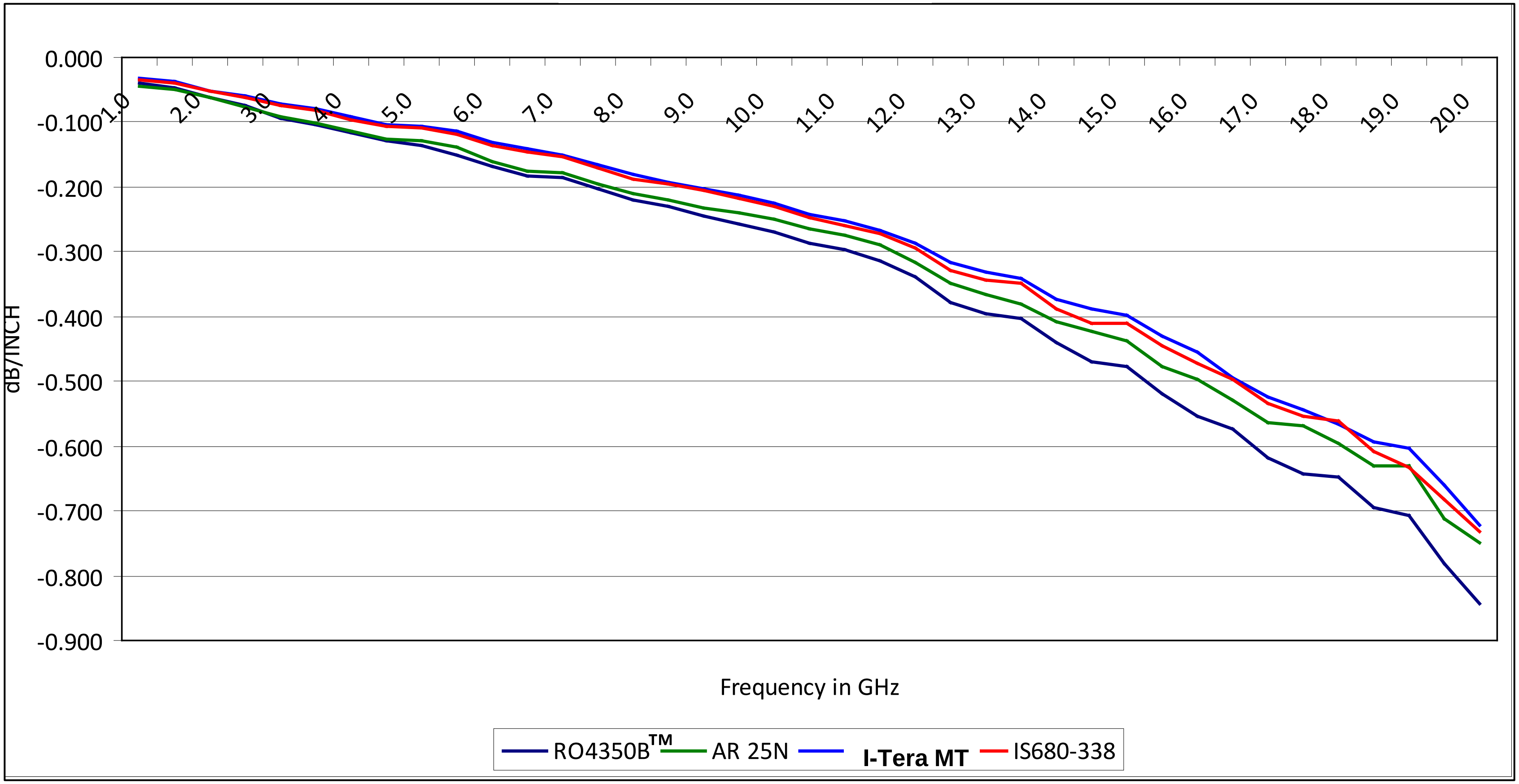
I-Tera® MT Thermal Coefficient of Dielectric Constant



I-Tera® MT Thermal Coefficient of Loss Tangent



I-Tera® MT & IS680 vs. Competitive Products



20-25% Improved performance over the competition!

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Astra® MT

Astra® MT

- **RF/Microwave Applications**
  - Automotive RADARs and sensors - 77 Gigahertz
  - DAS antennas
  - CPE antennas
  - Feed networks
  - Point to point – microwave links
  - mm-wave applications
  - Aerospace applications
  - GPS satellite antennas

- **Competitive products**
  - Rogers RO3003™ high frequency circuit materials
  - Taconic ORCER RF-35
  - Arlon AD300C

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Astra® MT Product Offering

- **RF/microwave and mm wave applications**
  - Dk: 3.00
  - Core thickness available: 0.005”, 0.010”, 0.015” 0.020”, 0.030” and 0.060”
  - Copper: HVLP-2 (2 micron) copper foil

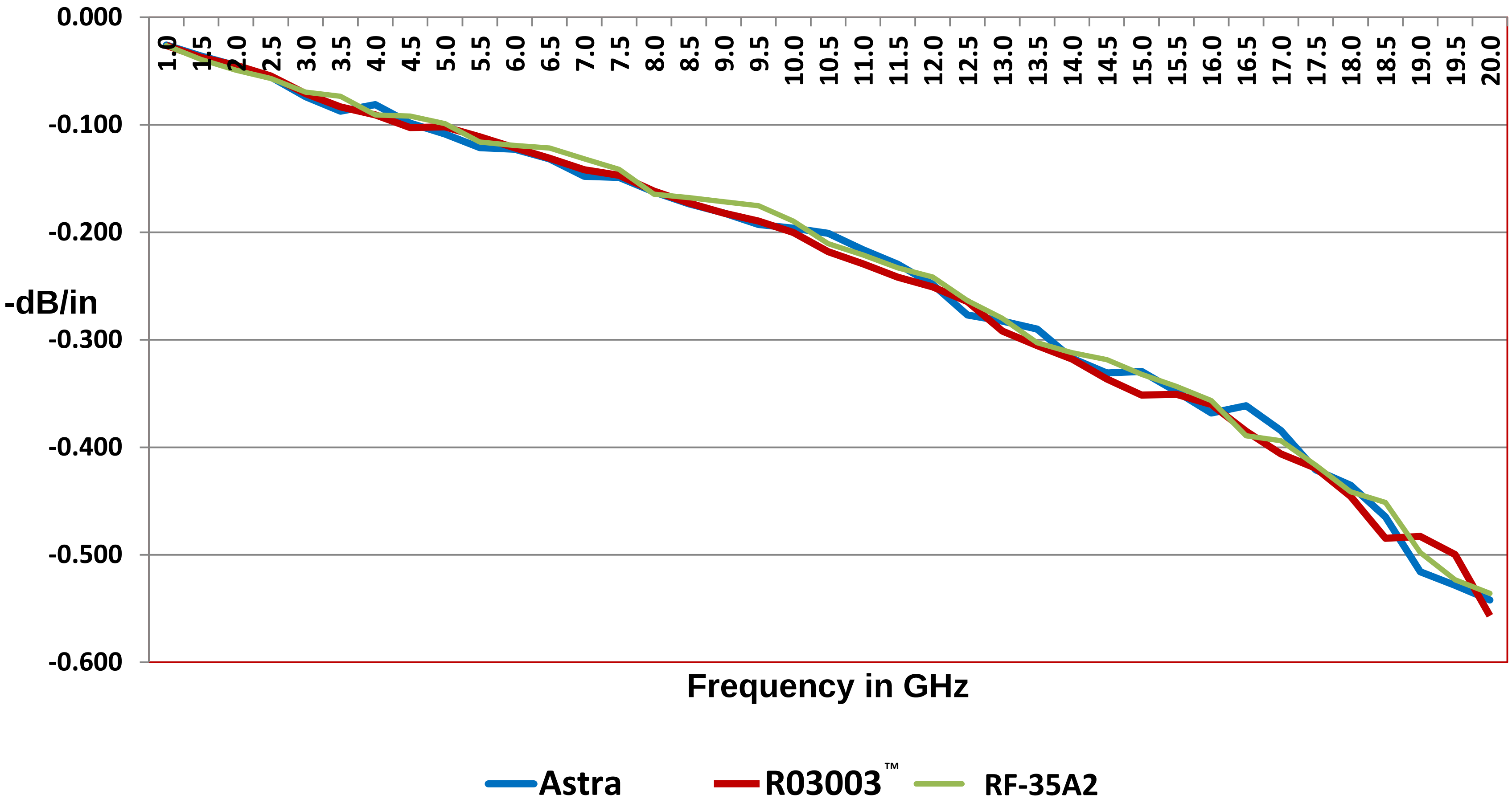
Astra® MT Key Properties

Property	Units	Astra MT
Tg, (DSC)	C	200
Td, (TGA)	C	360
CTE - z-axis (50-260°C)	%	2.80
T-260 (TMA)	minutes	60
T-288 (TMA)	minutes	> 60
Dk - 2 GHz		3.00
Dk - 5 GHz		3.00
Dk - 10 GHz		3.00
Df - 2 GHz		0.0017
Df - 5 GHz		0.0018
Df - 10 GHz		0.002
Peels, 1 oz after thermal stress		5
Moisture Absorption	%	0.01
Flammability	-	94 V-0
UL recognition		non Ansi

Astra MT

Testing at 77 and 100 GHz

Astra® MT vs. Competition



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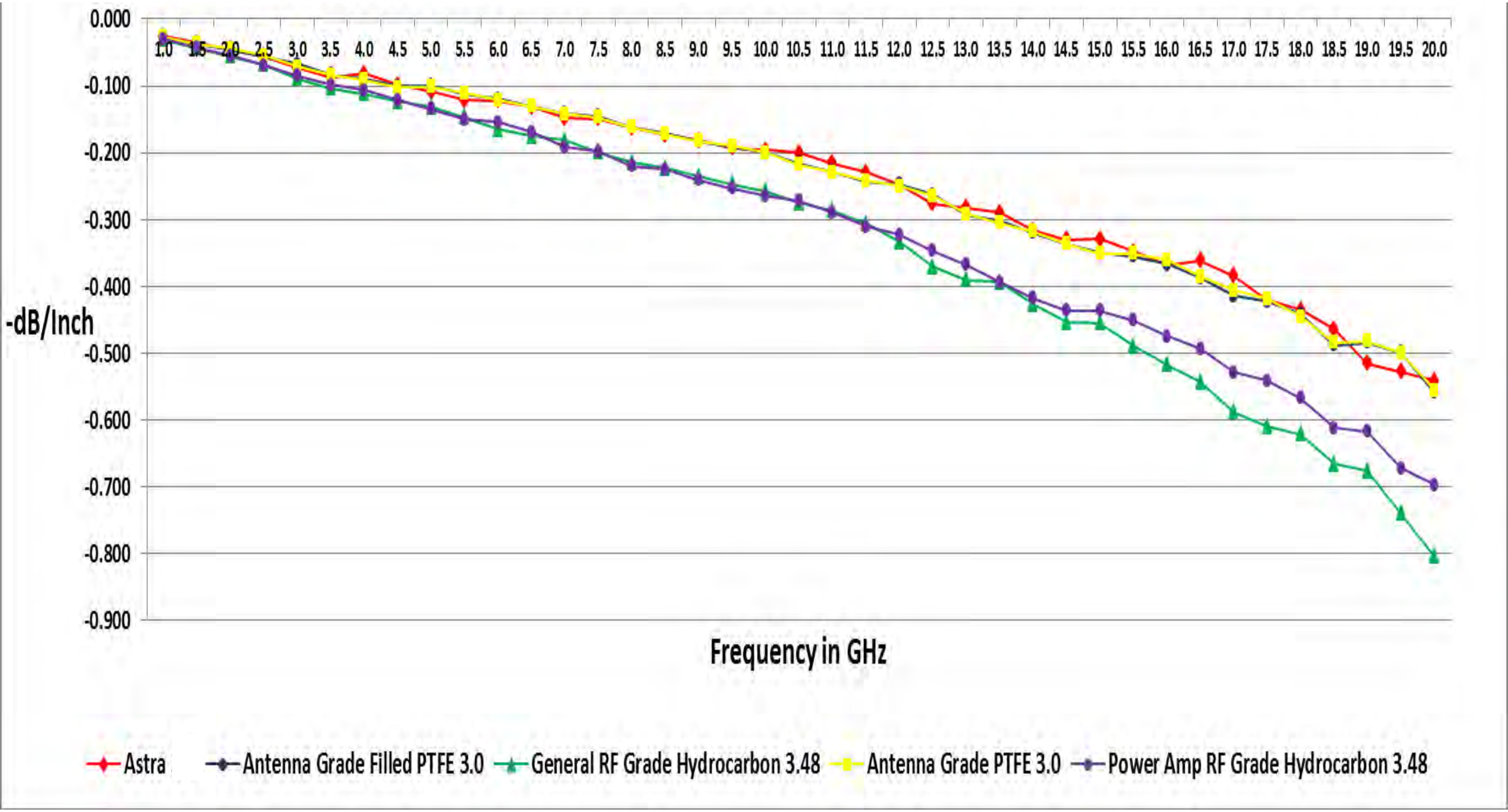
Astra® MT vs. Competition Attenuation –dB/Inch



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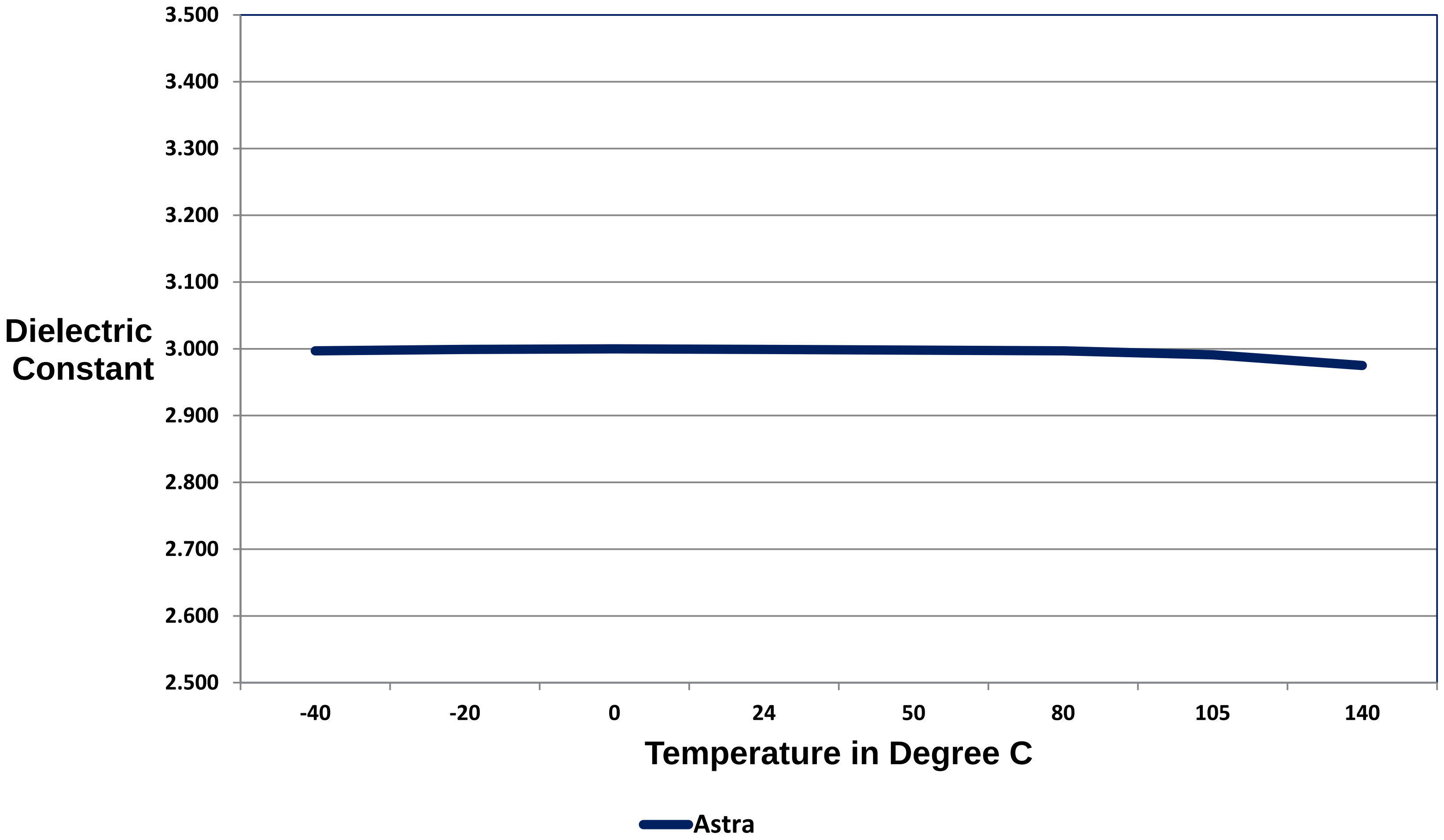
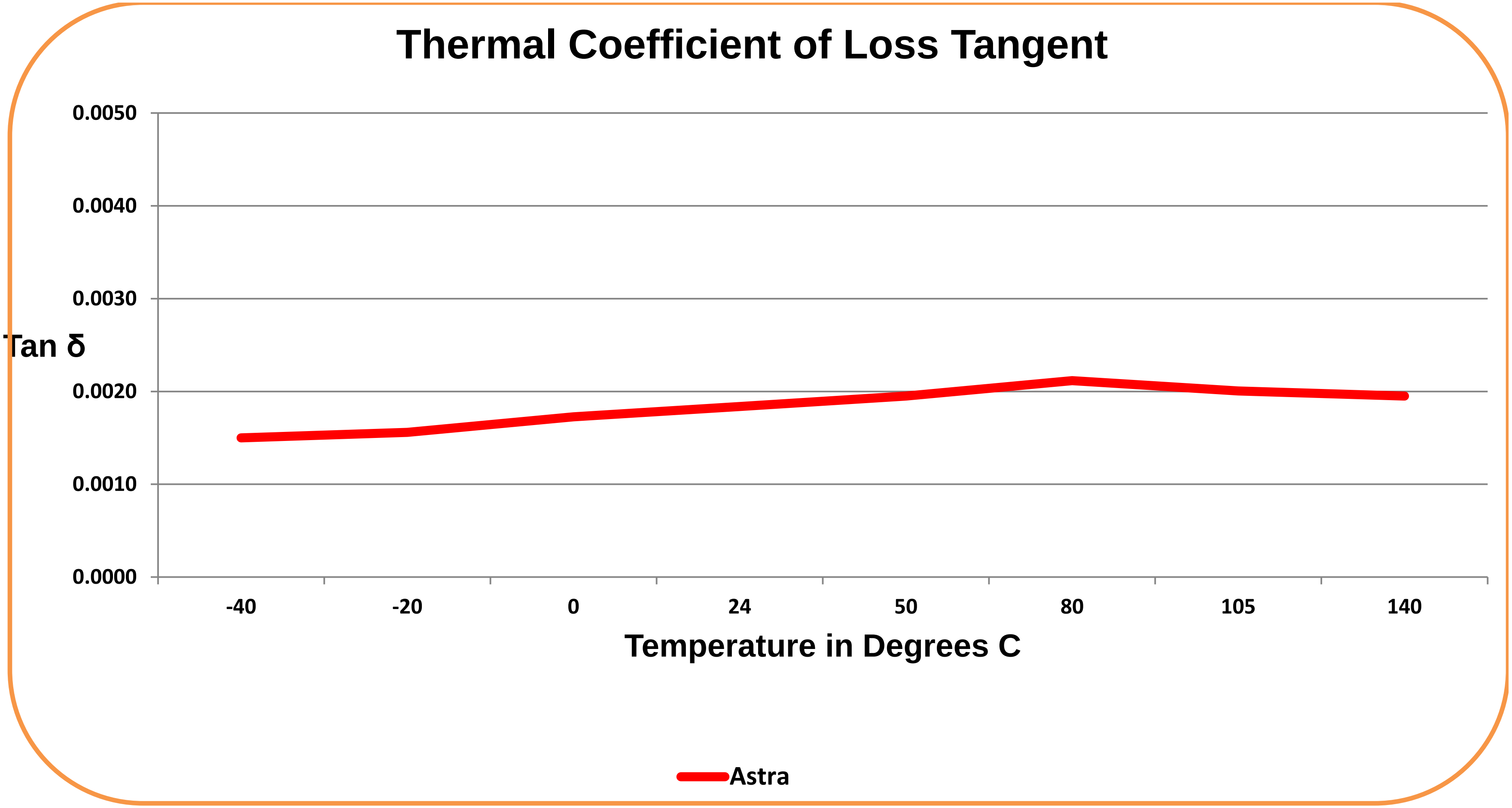
Astra® MT TCk -40°C to 140°C



Astra offers very stable Dielectric Constant (Dk) over temperature due to its high Tg

Astra® MT Thermal Coefficient of Df



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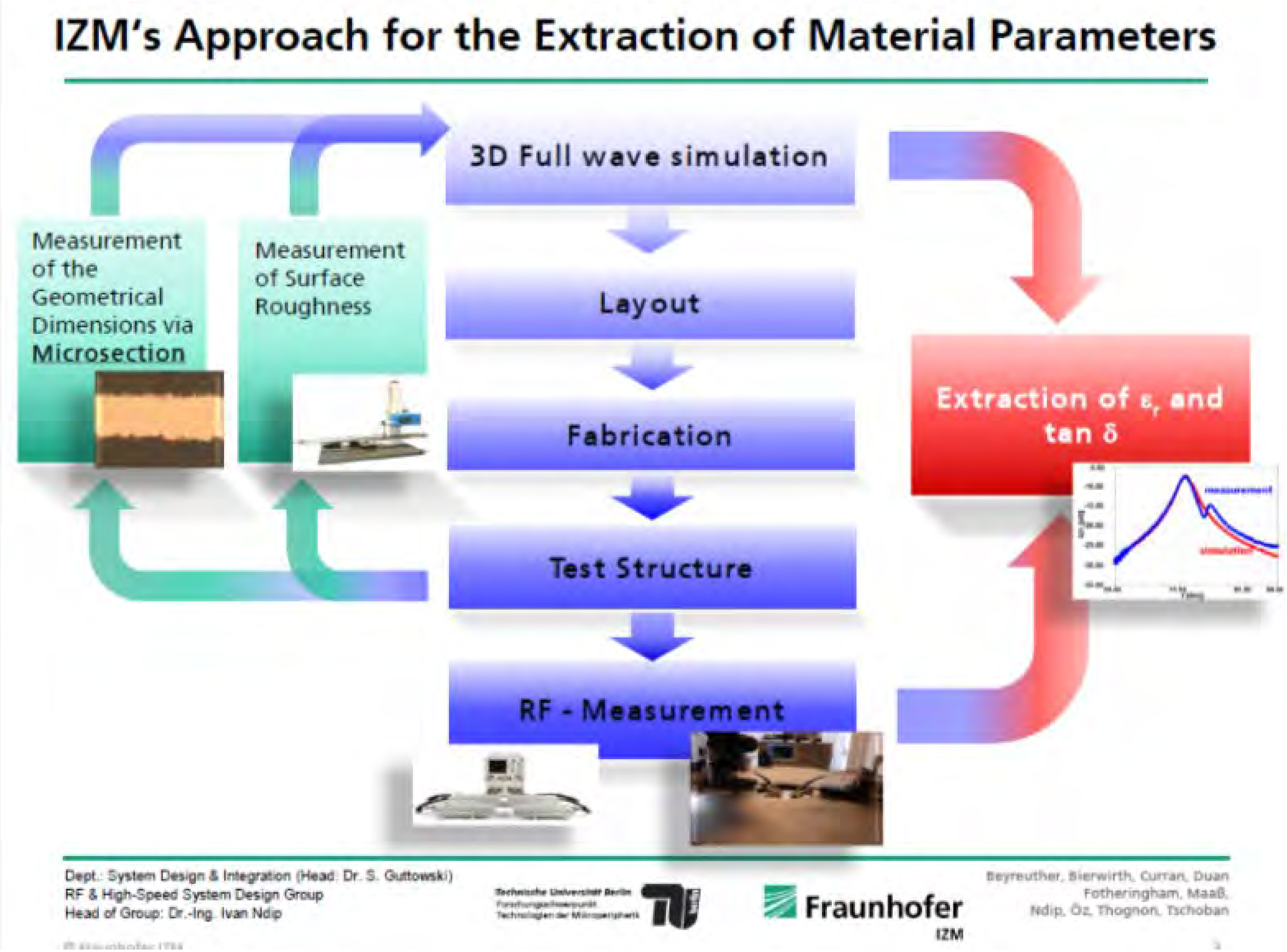
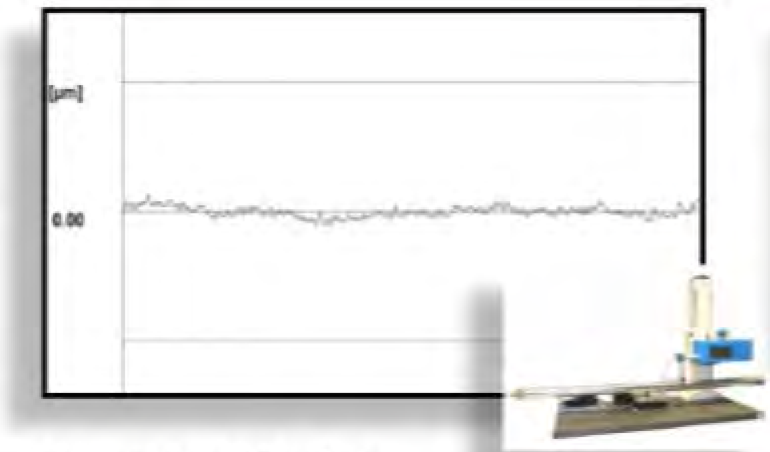
Astra® MT Testing at 77 & 100 GHz

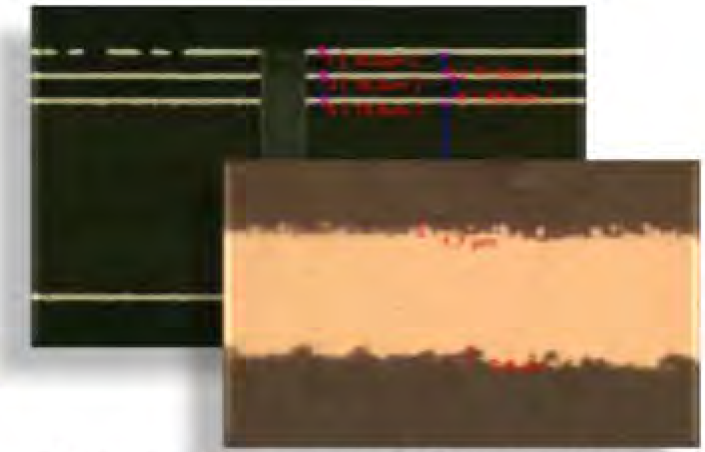


Astra® MT Testing at 77 & 100 GHz

Adaptation of 3D Simulation Models



Measurement of surface roughness using a *Hommel Profilometer*



Geometrical measurement of cross-section and optical measurement of the surface roughness parameters (microsection)

Impact of surface roughness and geometrical fluctuations during fabrication were considered in HFSS simulations. For the surface roughness, the Huray model was used

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Head of Group: Dr.-Ing. Ivan Ndip

Fraunhofer IZM

Beyreuther, Bierwirth, Curran, Duan
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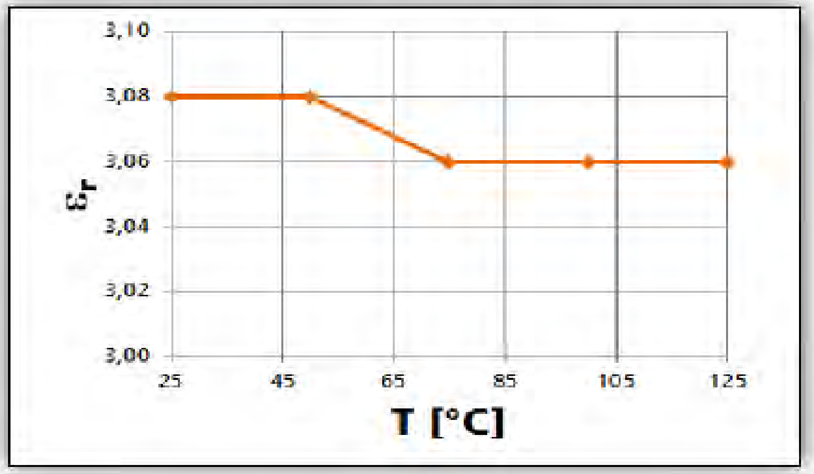
Astra® MT Testing at 77 & 100 GHz

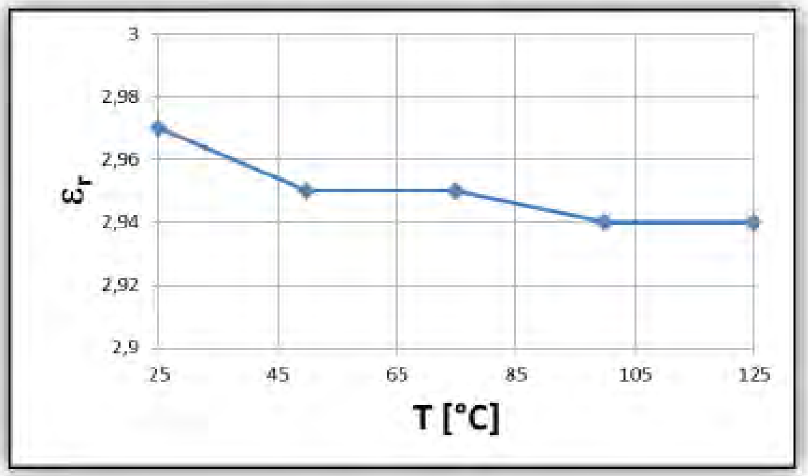
Extraction of the Dielectric Material Properties – 6/7

Permittivity Vs Temperature at Frequency Bands of Interest

76 GHz – Band



102 - 103 GHz – Band



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Astra® MT Testing at 77 & 100 GHz

Extraction of the Dielectric Material Properties – 7/7

➡ Typical Uncertainty

Extracted Values (25°C, 100GHz)

Test Structure	ε_r	$\tan\delta$
Resonator 1	2.97	0.0010
Resonator 2	2.96	0.0015

ε_r	$\tan\delta$
3.0 ± 0.1	$0.0015 \pm 5 \times 10^{-4}$

Considering typical uncertainty

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Astra® MT

- **Astra MT has been used in automotive 77 GHz hybrid board designs with Isola 185HR & 370HR**
- **Astra MT was processed with the Isola 370HR processing parameters with very good results**
- **Processing advantages:**
  - Predictable scaling (Competition does not use glass weave)
  - Microvia and drill processes used 370HR parameters and had standard hit counts vs reduced hit counts with the competitive products
  - Plasma desmear is not required
  - Astra MT does not need to be processed in a certain time period at microvia plating, electroless and soldermask processes.
    - Competitive products need to go through these process steps in a certain amount of time or will need to repeat the plasma process
  - Planarization of Astra MT is similar to FR-4

Selecting the Right Material

- **Laminate material selection can not be condensed into a single-page chart for easy selection**
- **High-performance laminate material suppliers have a better understanding of material performance**
- **Cost-to-performance evaluations must still be done by the system design team to ensure the lowest cost material that will do the job is selected**

Summary

- Printed Circuit Board (PCB) attributes for RF, microwave, millimeter-wave systems
- Application example – Advanced Automotive Safety System
- PCB material product solutions